High-Speed Optical Object Recognition Processor With Massive Holographic Memory

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ABSTRACT

Real-time object recognition using a compact grayscale optical correlator will be introduced. A holographic memory module for storing a large bank of optimum correlation filters, to accommodate the large data throughput rate needed for many real-world applications, has also been developed. System architecture of the optical processor and the holographic memory will be presented. Application examples of this object recognition technology will also be demonstrated.

1. INTRODUCTION

To date, optical correlator [1-3] has been extensively developed and applied for pattern recognition. JPL has recently developed, for the first time, a compact grayscale optical correlator (GOC) for real-time automatic target recognition (ATR). As shown in Figure 1, this optical correlator employs a Liquid Crystal Spatial Light Modulator (LC SLM), with 8-bit grayscale resolution for input incoherent-to-coherent image conversion. In the Fourier transform plane, a bipolar-amplitude (i.e. real-valued) SLM is used to encode correlation filter.

The utilization of a grayscale input SLM has enabled the direct input from the imaging sensor. This has alleviated the time-consuming preprocessing operations (e.g. edge enhancement and binarization) needed by the conventional binary correlators. The real-valued correlation filter encoding capability has enabled the use of a very powerful optimum filter computation algorithm, Maximum Average Correlation Height (MACH)[2,4], for distortion invariant correlation computation.

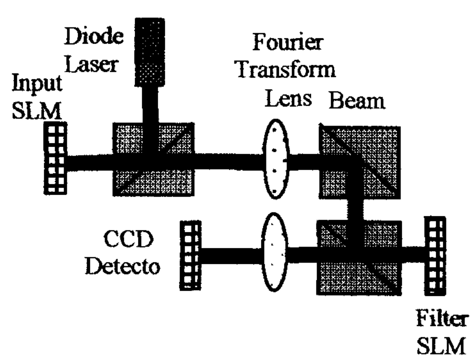


Figure 1. Schematic diagram of a Grayscale Optical Correlator using a diode laser source and a pair of reflective type Spatial Light Modulators.

Table I. Performance specifications of a pair of Spatial Light Modulators used in JPL's 512 x 512 Grayscale Optical Correlator

	Speed	SBP	Grayscale Resolution	Modulation	Pixel Pitch
Input SLM (FLC)	1000 Hz	512 x 512	8 bit	Positive- Real	7 μm
Filter SLM (FLC)	1000 Hz	512 x 512	4 bit	Bipolar - Amplitude	7 μm

The MACH algorithm was originally developed by Raytheon Missile Systems Co. In 1998, JPL demonstrated the first optical MACH correlation filter and its ATR applications. Merits of the MACH correlation include: a MACH filter is desired to generate an output correlation plane that has a high-peak response with respect to all input images from the same class; The filter maximizes the height of the mean correlation peak relative to the expected distortion (e.g. scale, rotation, perspective angle, etc.); The superior performance of MACH filter is attributed to its unique capability of reducing the filter's sensitivity to distortions and the removal of hard constraints on the peak that permits the optimization of performance criterion. Originally, the MACH filter is of complex-value. JPL has modified it into real-value during optical implementation to accommodate the modulation characteristics of the real-axis FLC SLM.

It has been identified that the key factor determining the volume of a GOC is the pixel pitch of the input and the filter SLMs. The volume will shrink nonlinearly with that of the pixel pitch of the SLM. For example, the volume of a previously developed 128 x 128 GOC utilizing a pair of 40-μm SLM is of the size of a camcorder (with multiply folded light path). By reducing the pixel pitch to 7-μm, the volume could be reduced by more than 50 times to that of a matchbox.

In order to continue the development of compact GOC for various object recognition applications, JPL has collaborated with BNS Inc. to develop a 7-μm pitch 512 x 512 FLC SLM. This SLM could be modulated in either positive-real value or bipolar-amplitude value (i.e. real-value). Thus it could be used both as the input or the filter SLM in a GOC. Recently. The contrast of this device is more than 100:1. The speed will vary with the type of FLC material utilized. It can reach a maximum speed of 1000 Hz. We have designed an innovative GOC architecture such that the system alignment could be greatly simplified and the tolerance of the focal length of the Fourier transform lenses is greatly relaxed. The experimental result demonstrated the validity of this new GOC design will also be presented. Table I shows the features of the two SLMs used in our new 512 x 512 GOC. The performance characteristics of the new 512 x 512 FLC SLM is listed in Table I.

2. COMPACT GOC SYSTEM DEVELOPMENT

A schematic diagram of the compact GOC, recently developed at JPL is shown in Figure 2. The traditional 4-f design has been modified to ease the dimension tolerance of optics and provide great flexibility in system alignment. A diode laser coupled with a collimator is used as the light source. The wavelength of the laser is 640 nm. The laser beam is first turned 90° by a mirror and then sequentially passed through a Fourier transform lens, a polarizing cubic beam splitter (#1) and a half-wave plate before impinging upon the 512 x 512 FLC input SLM. The readout beam, reflected out by the input SLM, then passes sequentially through two cubic polarizing beam splitters (#1 and #2), a second half-wave plate before reaching the 512 x 512 FLC filter SLM. The readout beam, reflected from the filter SLM, possesses a complex light modulation that is proportional to the product of those of the optical Fourier transform of the input image and the correlation filter. This readout beam passes thorough the beam splitter (#2), a compound inverse Fourier transform lens and is then picked up by an Active Pixel Sensor (APS). The compound Fourier transform lens is a pair lens (all positive, or one positive and one negative, depending on design parameters). The APS picked up the light distribution of the correlation plane of the optical correlator.

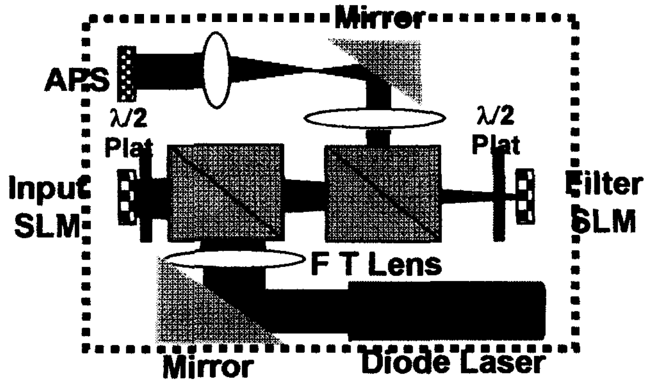


Figure 2. Schematic diagram of a Grayscale Optical Correlator using a pair of reflective type 512 x 512 FLC SLM.

The key new feature of this GOC architecture is the placement of the input SLM behind the Fourier transform lens. It is well known that by doing so, the scale of the Fourier transform of the input image will be linearly proportional to the distance between the input SLM and Fourier transform plane (i.e. back focal plane of the FT lens).

The primary adevantage of the approach used in our GOC design over that of the conventional 4-f architecture is the great ease in the stringent precision requirement of the FT lens. As illustrated in equation 1, the focal length is dependent upon the wavelength of the diode laser. This wavelength may vary from device to device within a few nanometers. Thus with the 4-f architecture, very precisive sorting of laser diode has to be accommodate the custom made focal length.

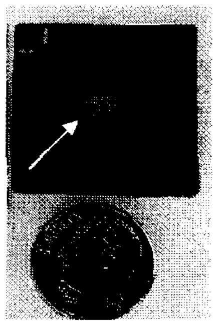
During system alignment, first all SLMs, optics, beam splitters, and half-wave plates were placed as shown in figure 1. Then, the input SLM was linearly moved along the optical axis until the scale of the Fourier transform reaches 3.584 mm (i.e. the aperture size of the SLM: 512 x 7 μm). This measurement is easier to be accomplished by monitoring the separation between the two first orders of diffraction over the back focal plane. This separation must be 7.168 mm when the alignment is done.

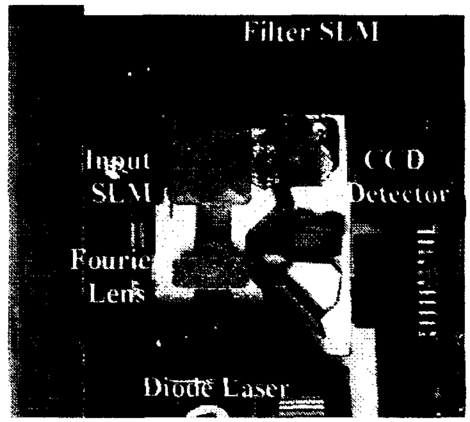
After the Fourier transform scale has been calibrated, the remaining optics devices and components (a pair of spatially separated lens, mirror, a beam splitter, and an APS) will be aligned until a sharp correlation peak(s) was observed from the APS output. Iterative alignment had to be conducted to ensure the system magnification is 1:1 between the input and the output plane such that precision target location was identified.

For illustration, a photo of the 7-μm pixel pitch, 512 x 512 FLC SLM is shown in Figure 3(a). A photo of a 512 x 512 GOC breadboard, built according to the schematic depicted in Figure 1, is shown in Figure 3(b).

One of the major limitations for more versatile ATR using this GOC is the severe limitation in electronic memories. This GOC is capable for updating the correlation filter at a rate of 1000 frames/sec. Each filter consists of 512 pixel x 512 pixel with 8-bit grayscale resolution. Thus, to operate the correlator at full speed, the filter data throughput will be at 2 Gbs/sec. This transfer rate is far beyond that of magnetic hard disk. Only SDRAM could be used with adequate data transfer rate. However, to save a modest number of 1000 filters on-board, it would need a 2 Gbs of SDRAM memory. The memory board size and power consumption is too excessive for many air and space-borne system to accommodate. Therefore we have looked into holographic memory [3] as an alternative memory solution for real-time pattern recognition using a GOC.

Unique advantages of using holographic memory system for updatable optical correlator applications including high storage density, random access, high data transfer rate, and grayscale image storage capability. All these three characteristics very well meet the memory requirements of a GOC.





3(a) 3(b)

Figure 3. A photo of a 7-μm pixel pitch, 512 x 512 FLC SLM is shown in 3(a), an arrow pointing to the SLM with the aperture size of 3.58 mm x 3.58 mm. A photo of a 2" x 2" x 1", matchbox-sized GOC is shown in 3(b)

3. HOLOGRAPHIC MEMORY SYSTEM FOR CORRELATION FILTER UPDATE

JPL has developed new Random Access Memory (RAM) that would simultaneously satisfy non-volatility, rad-hard, long endurance as well as high density, high transfer rate, low power, mass and volume [5-6]. The holographic memory architecture is shown in Figure 4. Collimated laser beam first enters PBS_1 (polarizing beam splitter 1) and on exit, is split into two beams. The input beam subsequently passes through the data SLM (spatial light modulator), L_3 (lens 3) – M_1 (mirror 1) – M_2 – M_3 – L_4 and then reaches the PRC (a Fe: LiNbO3 photorefractive crystal). The lens pair L_3 – L_4 will relay the data SLM throughput image onto the PRC, the mirror set M_1 – M_2 – M_3 will fold and increase the light path length to make it equal to that of the reference beam. The reference beam, after exiting PBS_1, will subsequently pass through L_3 – PBS_2, -$BSSLM_1$ (Beam Steering SLM 1) - PBS_2 - L_3 – PBS_3 -$BSSLM_1$ – PBS_3 – L_4 and then reach the PRC. The data beam and the reference beam intersect within the volume of the PRC to form a 90° recording geometry. Both beams are polarized in the direction perpendicular to the incident plane (the plane formed by the reference and signal beams). L_3 – L_4 is a lens pair to relay the $BSSLM_1$ onto the PRC surface. BSSLM1 will scan the reference beam along the horizontal plane (or the x-axis) in parallel with the C-axis. $BSSLM_2$ will steer the reference beam in the vertical plane (y-axis, or the fractal plane). During holographic data recording, the interference pattern formed by each page of input data beam and the specifically oriented reference beam will be recorded in the PR crystal. The reference beam angle (and location) will be altered with each subsequent page of input data. During readout, the data beam will be shut down and the reference beam will be activated to illuminate the PR crystal. Due to the principle of holographic wavefront reconstruction, the stored page data, corresponding to a specific reference beam angle, will be readout. The readout data beam will exit the PRC and pass through M_4 and L_5 before reaching the Photodetector (PD) Array. Note that the lens set L_3 – L_4 – L_5 will relay the input SLM to the PD array. The magnification factor, caused by the lens set, is determined by the aspect ratio between the data SLM and the PD array.

3.1. 2-D ANGULAR-FRACTAL MULTIPLEXING SCHEME

As depicted in Figure 4, by using two 1-D BSSLMs cascaded in an orthogonal configuration, a 2-dimensional angular-fractal multiplexing scheme has been formed, for the first time, in a JPL developed breadboard setup to enable the high-density recording and retrieval of holographic data.

In experiments, holograms were first multiplexed with x-direction (in-plane) angle changes while y direction angle holds unchanged. After finish the recording of a row of holograms, we then changed the y direction (perpendicular to the incident plane) angle, and recorded the next row of holograms with x-direction angle changes. Both x and y angle changes are fully computer controlled and can be randomly accessed. Currently we have successfully performed the recording and retrieval of long video clips of high quality holograms using this compact breadboard.

Unique advantages of this E-O beam steering scheme include: absence of mechanical motion, high-transfer rate (1Gb/sec), and random access data addressing, low-volume and low power.

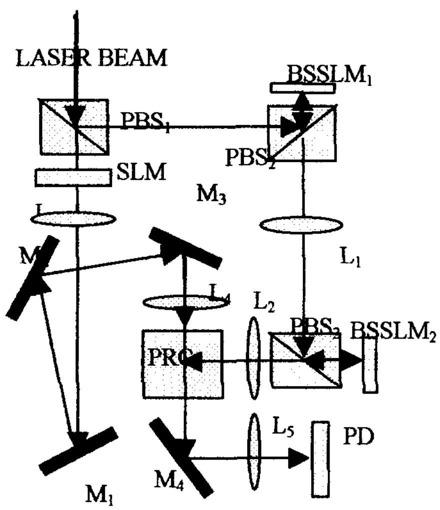


Figure 4. System architecture of compact holographic memory breading using a 2-D E-O angular-fractal multiplexing beam steering technology.

3.2. CD-SIZED COMPACT HOLOGRAPHIC MEMORY BREADBOARD WITH 2-D E-O ANGULAR-FRACTAL BEAM STEERING

JPL has recently developed a miniaturized CD-sized holographic memory breadboard. A photo of this breadboard is shown in Figure 5. The layout of this system follows the system schematic shown in Figure 4. This CD-sized holographic memory breadboard, measuring 10 cm x 10 cm x 1 cm, is the most compact holographic memory module developed to date. The compact size of the VLSI based BSSLM together with advanced optics design has enabled the drastic reduction in the system volume from book-size to CD-size. This breadboard is capable of recording 10 Gbs of holographic data. The current system design would make it possible the easy replacement of the key devices when a upgraded version becomes available. These key devices include the Spatial Light Modulator, the BSSLM, and the PD array. Moreover, the system storage capacity would be increased by up to 2 orders of magnitude when a high-resolution BSSLM is developed.

4. Experimental Demonstration of Optical Pattern Recognition Using Correlator Using Holographic Memory

We have conducted experimental investigations using JPL's compact GOC (5 cm x 5 cm x 2 cm in volume) for the application of agricultural pest recognition and classification. For this experimental demonstration, we have utilized agriculture pest samples as an example. We have utilized holographically retrieve grayscale image data to support the correlation filter need of a GOC. First, a set of training images, as shown in Figure 6(a) was selected for developing MACH correlation filters. A picture a corresponding MACH filter is shown in Figure 6(c). This MACH filter is of 8-bit grayscale and biased into positive-real value prior downloaded to the filter SLM. This MACH filter was first recorded into our holographic memory system and subsequently readout and downloaded into the filter driver of the GOC. The dynamic range of the retrieved holographic filter image was properly controlled to retain the 8-bit resolution.

After the holographically retrieved MACH filter image is downloaded into the filter SLM of the GOC, an input image consist of several types of agricultural pests was fed into the input SLM. Sharp correlation peaks associated with 5 pests of the same class (as marked and numbered in the input) in various orientations were successfully obtained from the correlation output. The correlation results are displayed in Figure 6(b).

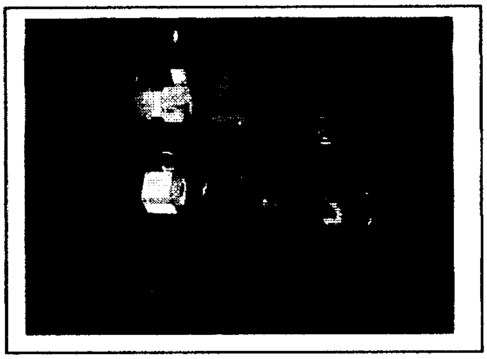
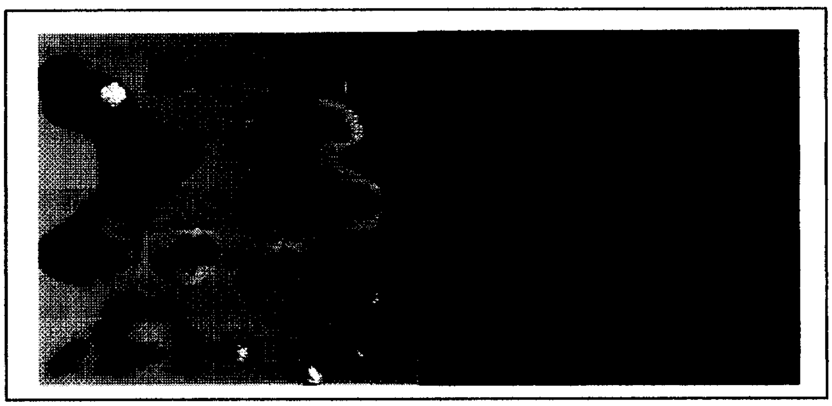


Figure 5. Photo of JPL Developed Compact Advanced Holographic Memory Breadboard of the size of a CD-sized (Volume of 10 cm x 10 cm x 2.5 cm, or 4" x 4" x 1") using a 2-D E-O Beam Steering Technology with an Angular-Fractal Multiplexing Scheme.

(a)



(b)

(c)

Figure 6. a) An example input image consisting of 5 classes of agriculture pests. b) Correlation peak detection output showing the simulation detection of the 5 pests of the same class. C) the MACH correlation filter used to perform the correlation detection.

5. SUMMARY

We have developed a compact GOC and a holographic memory system and have demonstrated object recognition using correlation filters retrieved from a holographic memory system. The unique high-density, high-transfer rate and random access characteristics of the holographic memory matches perfectly the onboard memory need of a GOC by supporting the high-speed, large throughput optical correlation filter requirements.

6. REFERENCES

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